

## Lecture 13 Entropy

(Sec.3.6 of Hess – 2<sup>nd</sup> Law of Thermodynamics)

[For classical equation editor: ( $dq = 0$ )]

- We have noted in earlier lectures that

$$\oint p d\alpha \neq 0.$$

in general. Also note that the amount of work done by the system is equal to the area enclosed by the contour representing the cyclic process in an  $\alpha$ - $p$  diagram.

- From the 1st law of thermodynamics,

$$dq = c_v dT + p d\alpha,$$

The amount of heat change for a cyclic process is

$$\oint dq = \oint p d\alpha \neq 0.$$

- Mathematically, this means  $dq$  is not an exact differential. However, if we divide the alternative form of 1st law,  $dq = c_p dT - \alpha dp$ , by  $T$ , then

$$\frac{dq}{T} = c_p \frac{dT}{T} - R \frac{dp}{p},$$

or

$$\frac{dq}{T} = c_p d(\ln T) - R d(\ln p).$$

This implies that

$$\oint \frac{dq}{T} = 0.$$

Therefore although  $dq$  is not an exact differential,  $dq/T$  is.

- Since  $ds$  is an exact differential, we may define a new variable  $s$  as

$$ds = \frac{dq}{T}$$

where  $s$  is called **entropy**, or more precisely **specific entropy**.

- Note that the concept of entropy is introduced from mathematical considerations, but as we will see, its **physical meaning** is related to the second law of thermodynamics.
- **Claim: Entropy is related to potential temperature.**  
[In fact, it can be stated that an isentropic process is an adiabatic process and vice versa.]

**Proof:** From the definition of potential temperature

$$\theta = T \left( \frac{p_o}{p} \right)^{R/c_p} .$$

Taking  $\ln$  and multiplying  $c_p$  of the above equation leads to

$$c_p \ln \theta = c_p \ln T + R \ln p_o - R \ln p$$

Differentiating the above equation gives

$$c_p d(\ln \theta) = c_p d(\ln T) - R d(\ln p) .$$

Because

$$ds = \frac{dq}{T} = c_p d(\ln T) - R d(\ln p)$$

we have

$$ds = c_p d(\ln \theta)$$

Or after integration

$$\Delta s = c_p \ln \theta + C ,$$

where  $C$  is a constant resulted from integration of the equation above.

This means that **entropy of a system is related to potential temperature**. For adiabatic processes, potential temperature is conserved, therefore, so is entropy. In other words,

entropy remains constant along an adiabat (constant  $\theta$  lines). For this reason, an **adiabatic process is also called an isentropic process.**

On an  $\alpha$ - $p$  diagram, we may draw isotherms (constant  $T$ ) and adiabats (constant  $\theta$ ). The isotherms are drawn according to the equation of state:

$$p\alpha = RT = \text{const.}$$

The adiabats are drawn according to the Poisson's equation, e.g.,

$$p\alpha^\gamma = \text{const.}$$

Since  $\gamma = c_p/c_v > 1$ , *adiabats are steeper than isotherms.*

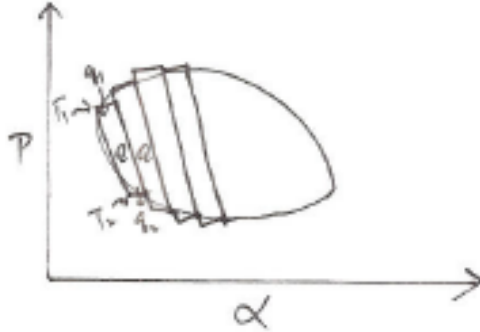
Consider the cyclic process ABCD in a Carnot cycle. In passing **reversibly** from one adiabat to another along an isotherm, heat is absorbed or rejected. Since  $q_2/q_1 = T_2/T_1$ ,

$$\frac{q_1}{T_1} = \frac{q_2}{T_2} = \text{const.}$$

This means that for the Carnot cycle, the ratio  $q/T$  is constant. Also, note that **the entropy is conserved in the Carnot cycle** since it is a cyclic process,

$$\oint ds = \oint \frac{dq}{T} = \frac{q_1}{T_1} - \frac{q_2}{T_2} = 0.$$

Any reversible processes can be considered as being made up of infinite number of Carnot cycle (see figure).

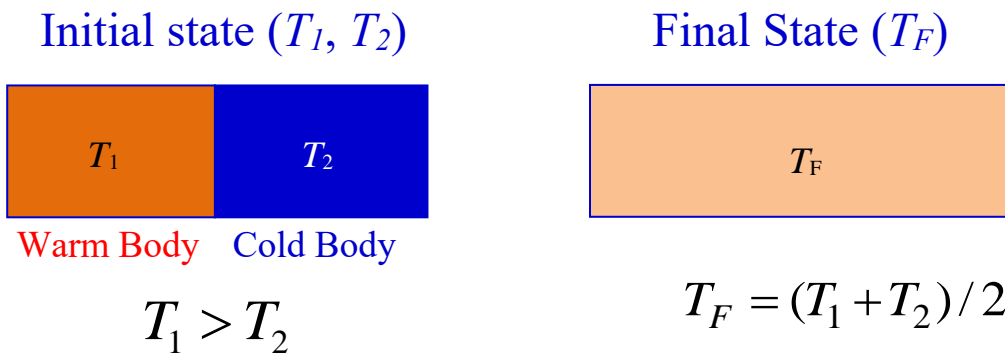


Thus, entropy does not change for any cyclic reversible processes.

Most of the real processes are irreversible. Thus, entropy changes.

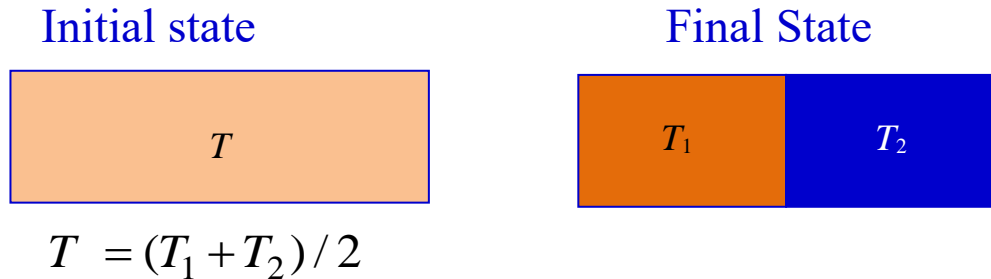
The direction of natural (real) processes is determined by the second law.

For example, let us consider two isolated ideal gases at temperatures of  $T_1$  and  $T_2$ , separated by some conductive, expandable material (such as membrane).



The thermodynamic equation  $dq=c_p dT-\alpha dp$  can be applied to individual gas, which leads to  $dq=c_p dT$  since  $p$  does not change in each part.

Now assume the reversible situation was tried:



The above process will not occur, yet it does not violate the first law. Thus, the first law does not tell us anything about the direction in which a natural process will take place.

Question: *Does entropy increase or decrease in a real (irreversible) process?*

The answer is that entropy can only be increased in a real (irreversible) processes. This can be proved more rigorously, however, we will simply use the above example to show it.

If  $T_1=290$  K and  $T_2=300$  K, then  $\bar{T}=295$  K. Therefore,

$$ds = dq/T = c_p dT/T, \text{ since } dq=c_p dT-\alpha dp=c_p dT.$$

This leads to

$$\Delta s = c_p \ln\left(\frac{T_f}{T_i}\right).$$

For the first process:

for gas 1:

$$\Delta s = c_p \ln\left(\frac{295}{290}\right) = 17.163,$$

for gas 2:

$$\Delta s = c_p \ln\left(\frac{295}{300}\right) = -16.874.$$

Thus, the sum of entropy is .287 J/kg-K, which is greater than 0.

Suppose the second process did take place, then

for gas 1:

$$\Delta s = c_p \ln\left(\frac{290}{295}\right) = -17.163,$$

for gas 2:

$$\Delta s = c_p \ln\left(\frac{300}{295}\right) = 16.867.$$

The sum of is  $\Delta s = -.296$ , which is less than 0.

The second law of thermodynamics may also be stated as:

Process in which the entropy of an isolated system would decrease do not occur.

Thus, we have

- Reversible processes:  $\Delta s = 0$  ( $s$  is constant)
- Irreversible processes:  $\Delta s > 0$  ( $s$  increases)
- Impossible processes:  $\Delta s < 0$  ( $s$  decreases)

Mathematically, we may express the second law of thermodynamics as that for an isolated system,

$$ds = \frac{dq}{T} \text{ for a reversible process}$$

$$ds > \frac{dq}{T} \text{ for an irreversible process.}$$

Or, for any processes in an isolated system, we have

$$ds \geq \frac{dq}{T}.$$

Since  $ds = dq/T$ , we may also write the second law as

$$ds \geq du + p d\alpha.$$

(3/29/18)